Searching for TMD-factorization breaking in p+p and p+A collisions: Color interactions in QCD

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INT Workshop on Transverse Spin and TMDs
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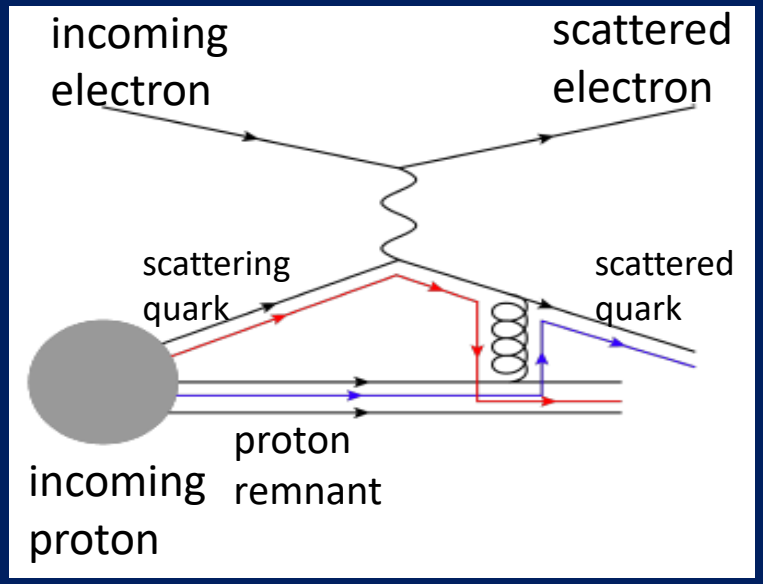
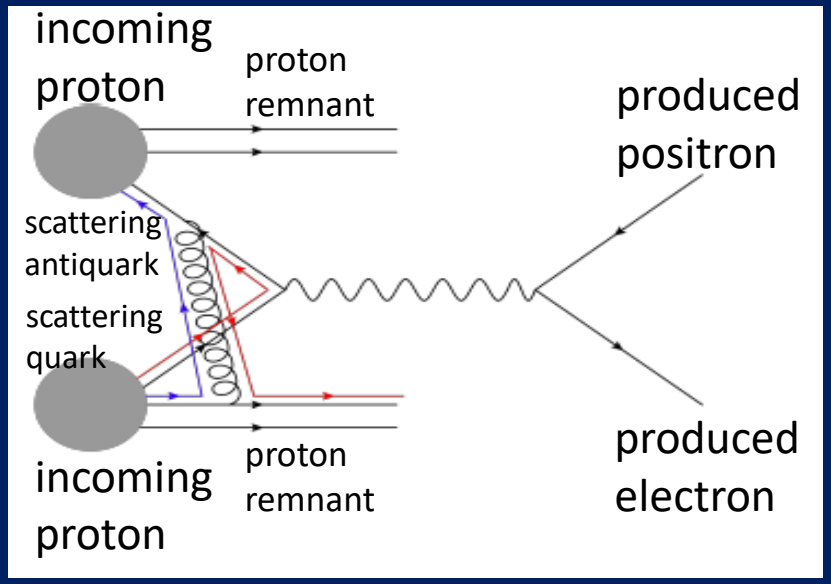
Modified universality of PT-odd correlations: Color in action!

Deep-inelastic lepton-nucleon scattering: Final-state color exchange



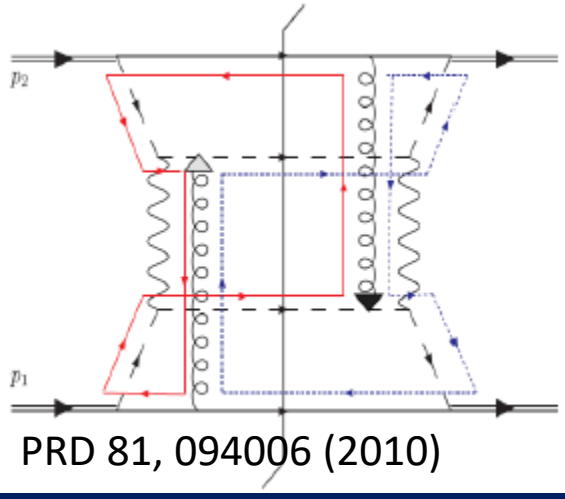
Quark-antiquark annihilation to leptons: Initial-state color exchange



***Opposite sign* for PT-odd transverse-momentum-dependent distributions measured in these two processes: *different color interactions* (Collins 2002)**

Extension to hadroproduction of hadrons: Non-Abelian effects → Color entanglement

- 2010: T.C. Rogers and P. Mulders predict *color entanglement* in processes involving proton-proton production of QCD bound states if nonperturbative transverse momentum taken into account
- TMD-factorization is broken, and partons become correlated *across* the two colliding protons
  - Novel QCD state!
- Consequence of QCD specifically as a ***non-Abelian*** gauge theory



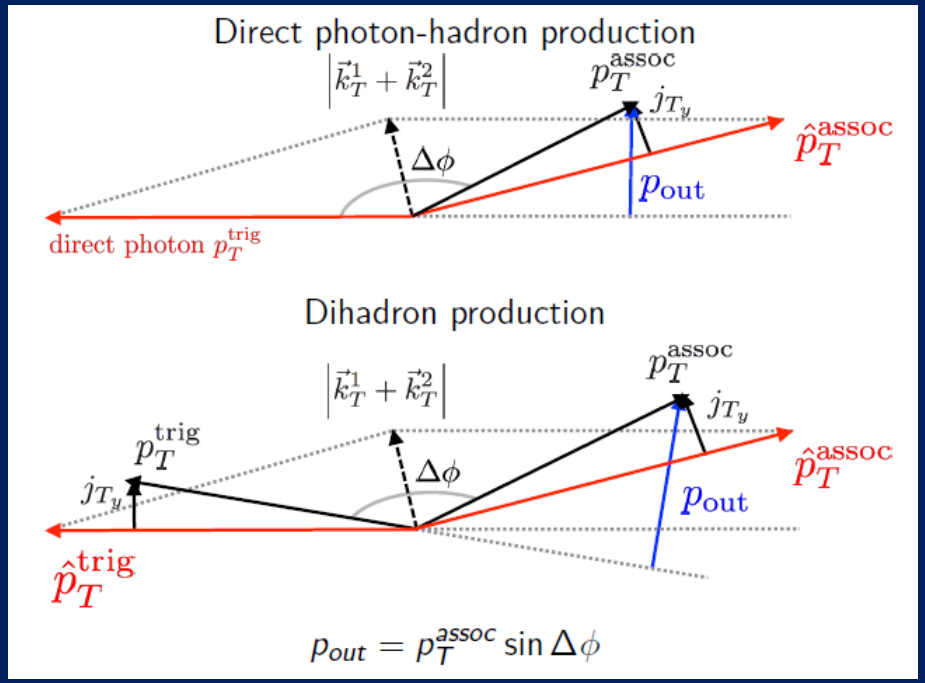
PRD 81, 094006 (2010)

$$p + p \rightarrow h_1 + h_2 + X$$

Color flow can't be described as flow in the two gluons separately. Requires presence of both.

Searching for evidence of color entanglement at RHIC

- Need observable sensitive to a nonperturbative momentum scale
  - Nearly back-to-back particle production
- Need 2 initial QCD bound states
  - color exchange between a scattering parton and remnant of other proton
- And at least 1 final QCD bound state
  - exchange between scattered parton and either remnant



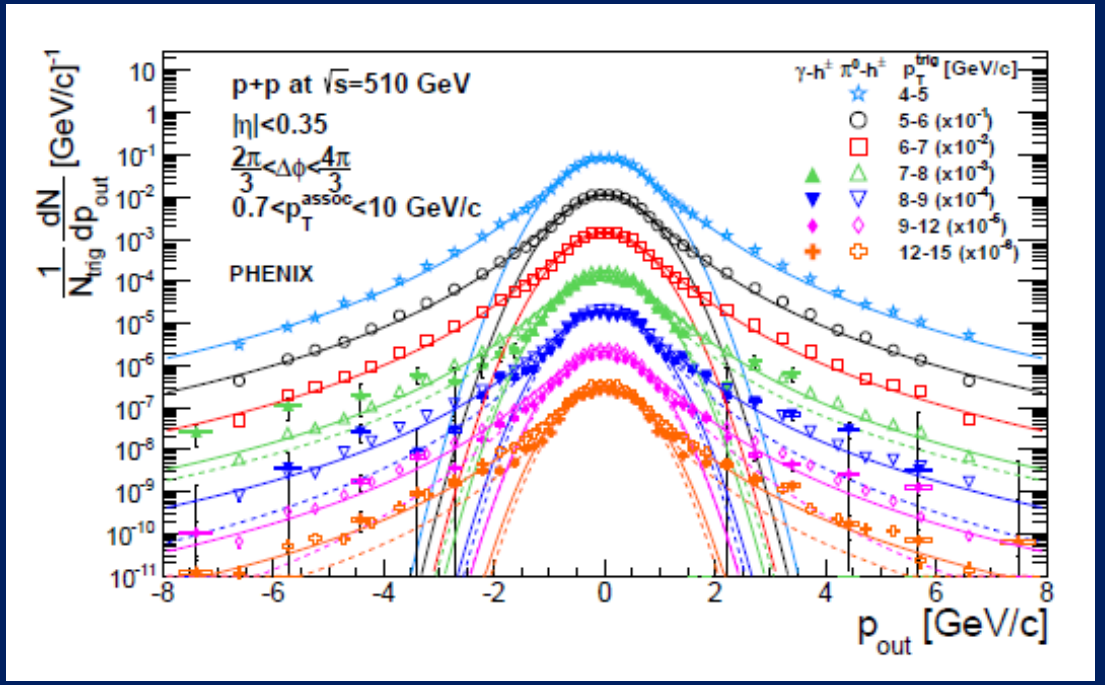
→ In p+p collisions at PHENIX, measure out-of-plane momentum component in nearly back-to-back photon-hadron and hadron-hadron production

- (Original) strategy: Compare out-of-plane momentum component distributions to calculations assuming TMD-factorization holds, and look for differences in shape and/or magnitude

Out-of-plane momentum component distributions

- Clear two-component distribution
  - Gaussian near 0—nonperturbative transverse momentum
  - Power-law at large p_{out}—kicks from hard (perturbative) gluon radiation
- Different colors → different bins in hard interaction scale

PRD95, 072002 (2017)



Curves are fits to Gaussian and Kaplan functions, **not** calculations!
No calculations were (or are) available, so . . .

*Try looking at **evolution** of nonperturbative transverse momentum widths with hard scale*

- Proof of TMD-factorization directly predicts that nonperturbative transverse momentum widths *increase* as a function of the hard scattering energy scale
  - Increased phase space for gluon radiation

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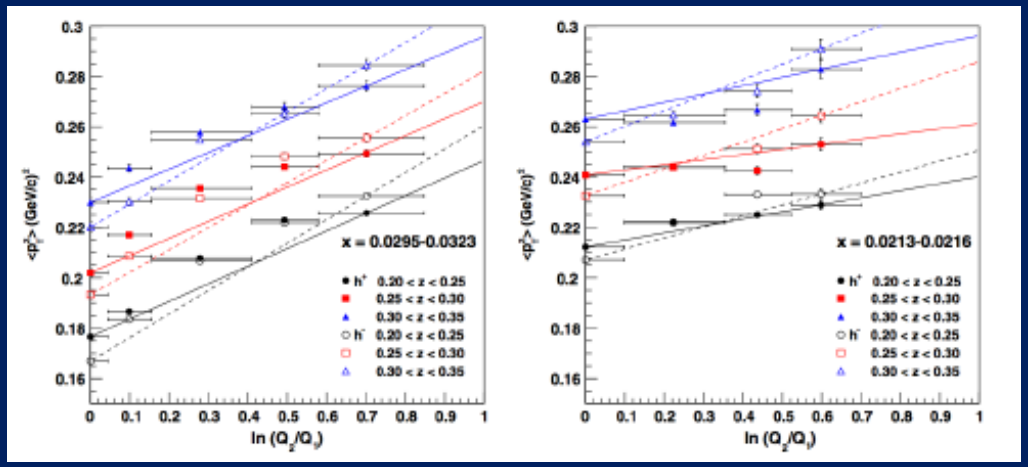
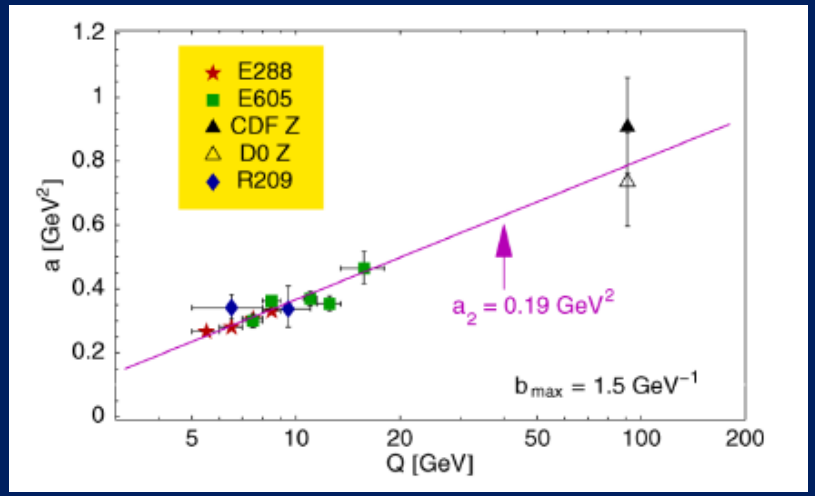
- Proof of TMD-factorization directly predicts that nonperturbative transverse momentum widths *increase* as a function of the hard scattering energy scale
  - Increased phase space for gluon radiation
- Confirmed experimentally in deep-inelastic lepton-nucleon scattering (left) and quark-antiquark annihilation to leptons (right)

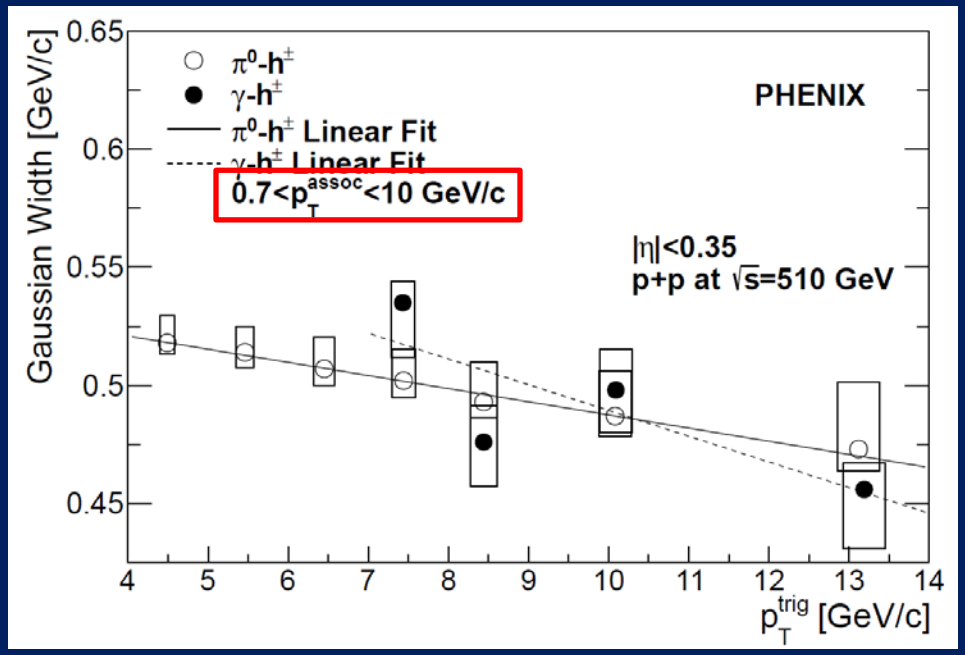


CAA, Field, Gamberg, Rogers, Phys. Rev. D89, 094002 (2014)



Konychev + Nadolsky, Phys. Lett. B633, 710 (2006)

*First paper (510 GeV p+p): Nonperturbative momentum widths may **decrease** in processes where entanglement predicted??*



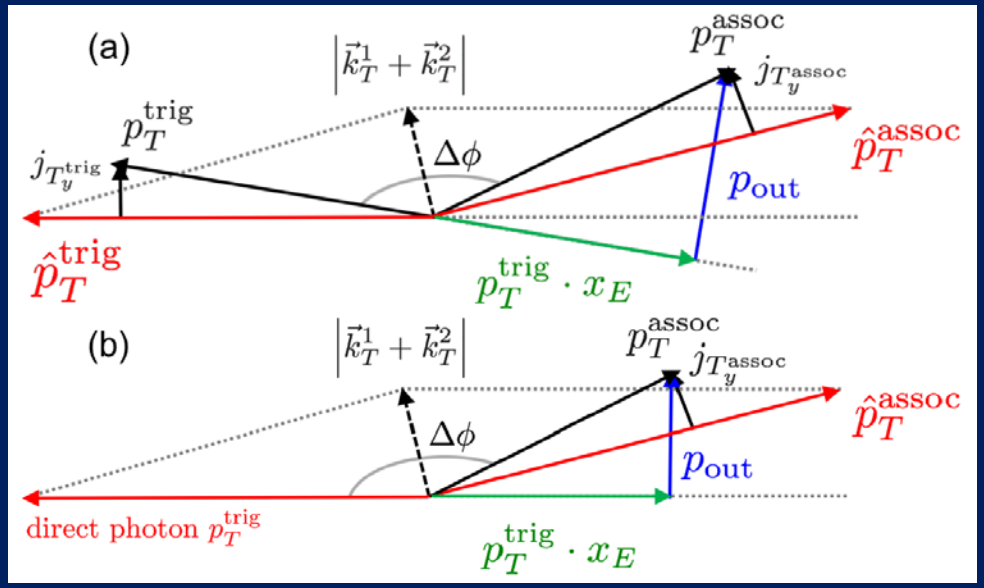
- Hint of different slopes for dihadron and gamma-hadron correlations – Due to different numbers of nonperturbative functions (2 vs. 1 FF), or different number of places to attach a gluon in the final state??
- However, have correlations among measured kinematic variables, e.g. x correlated with p_T^{trig} (hard scale proxy), varying p_T^{trig} for a fixed p_T^{assoc} range is changing z, …

PHENIX Collab., PRD95, 072002 (2017)

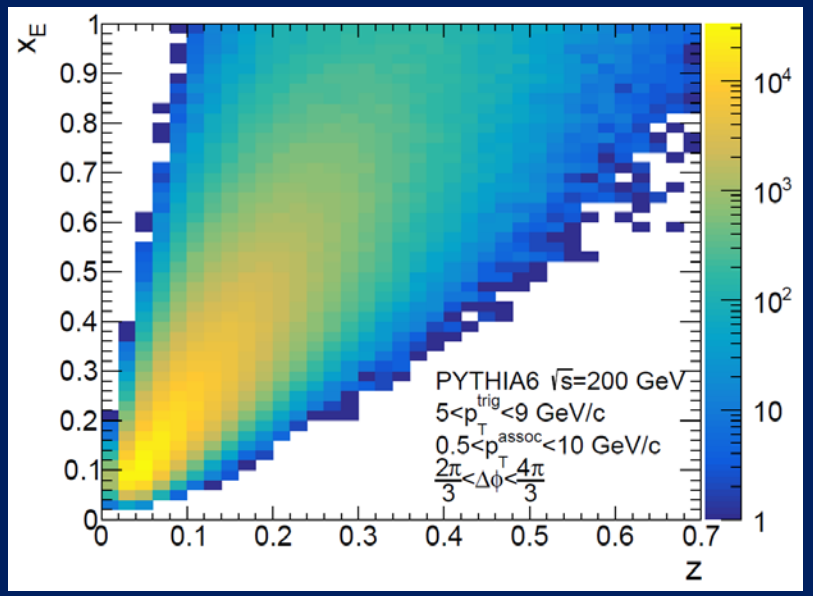
Second paper (200 GeV p+p): Try to get some handle on fragmentation z → Widths ***increase***

- Don't reconstruct jets, so use x_E as a proxy for z:

$$x_E \equiv -\frac{p_T^{\text{trig}} \cdot p_T^{\text{assoc}}}{|p_T^{\text{trig}}|^2} = -\frac{|p_T^{\text{assoc}}|}{|p_T^{\text{trig}}|}\cos\Delta\phi$$



arXiv:1805.02450, accepted by PRD



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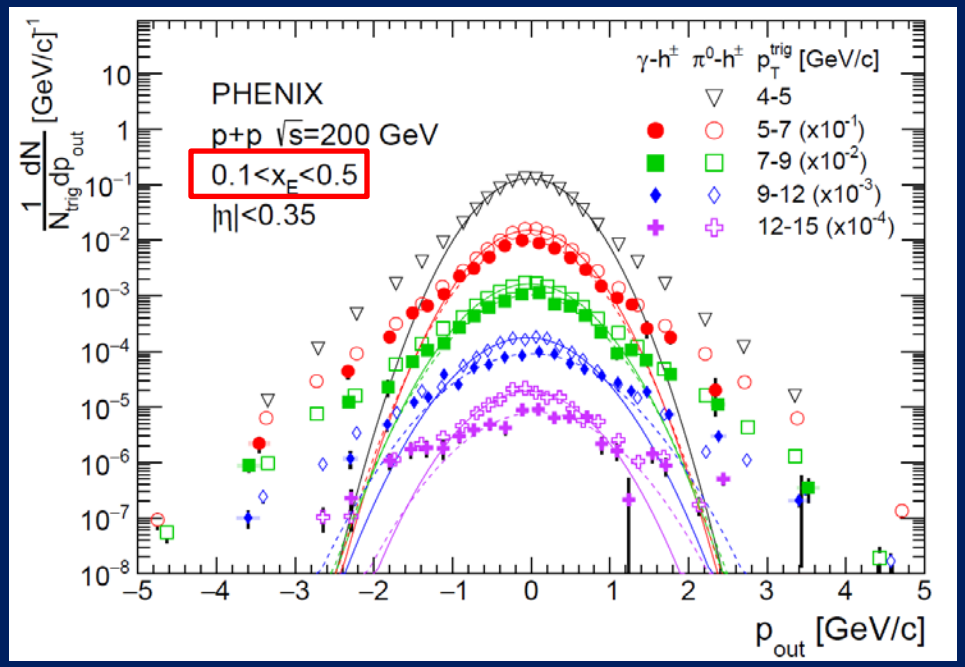

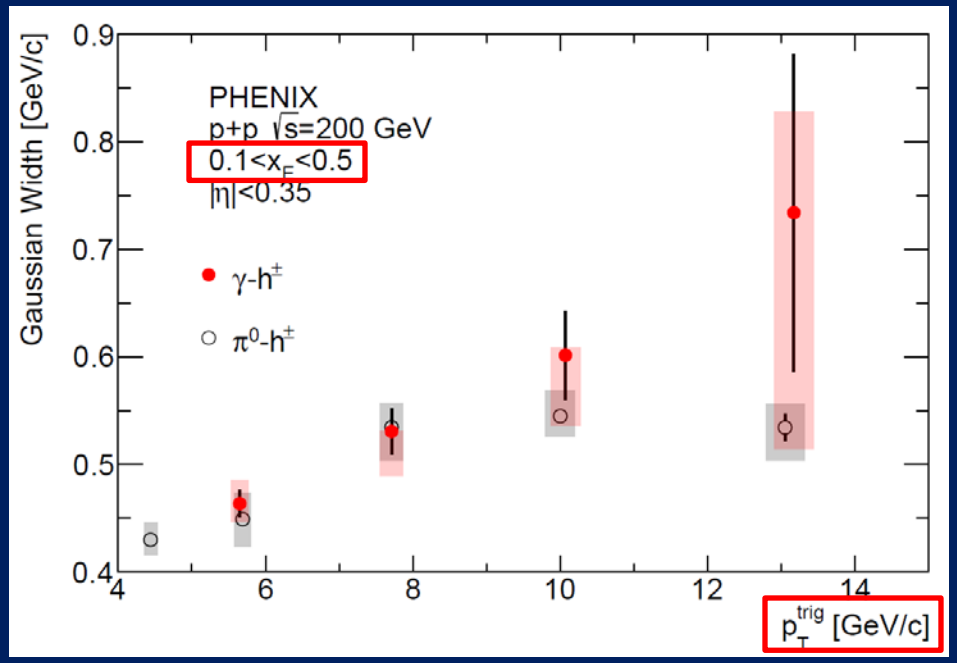

Fixed x_E range, different bins of p_T^{trig}

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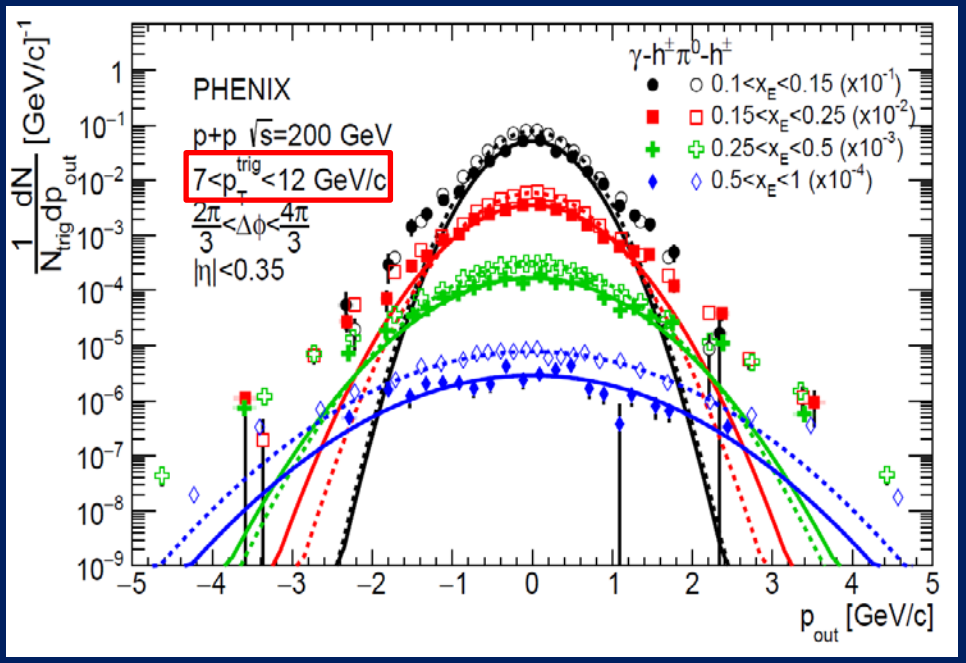

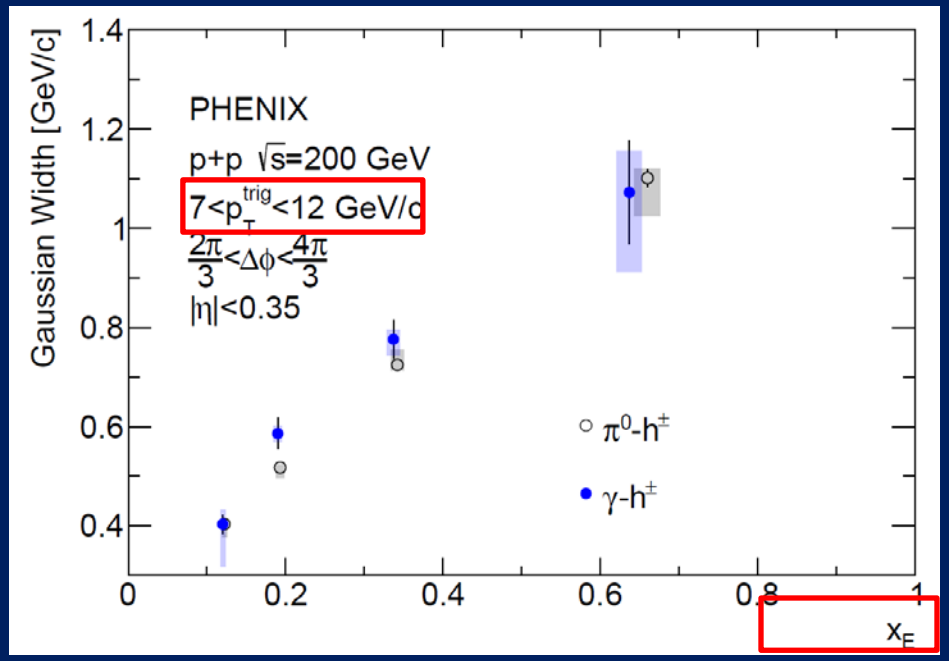

Fixed p_T^{trig} range, different bins of x_E

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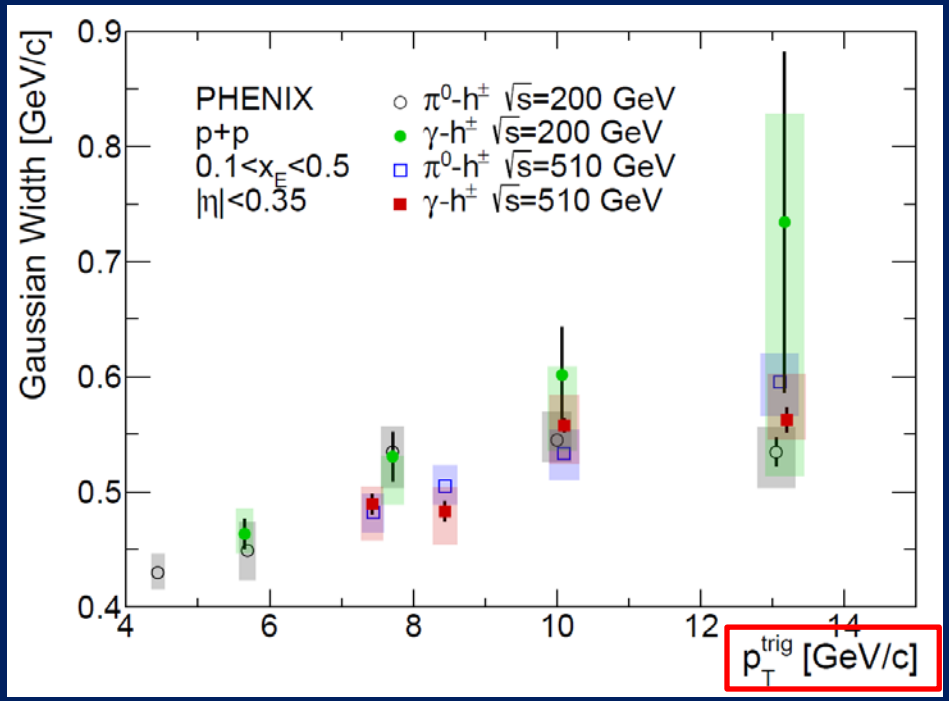
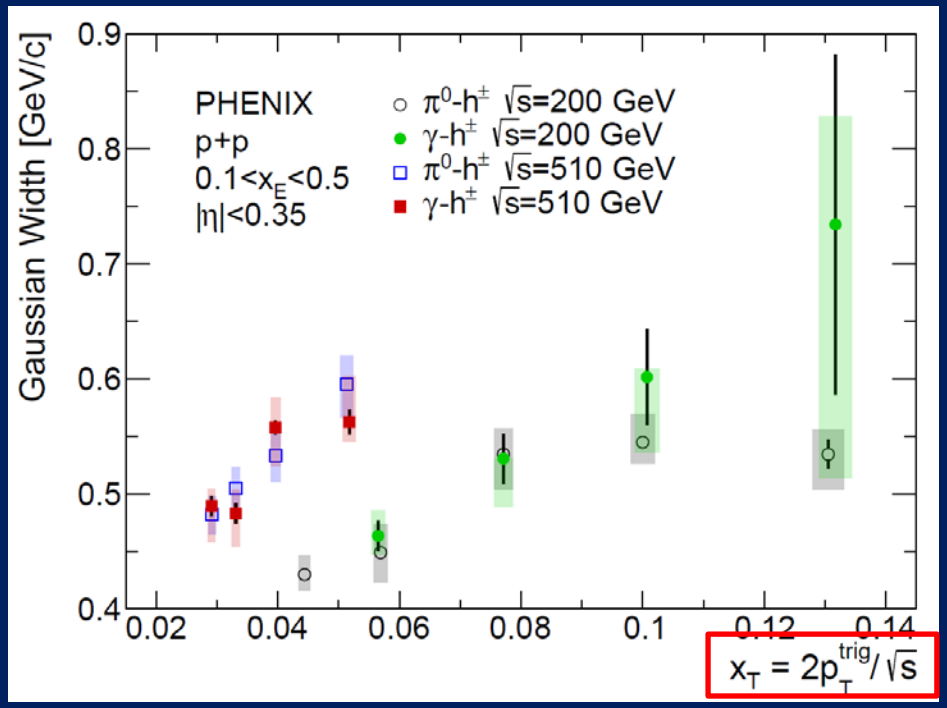
Second paper: Comparison of different sqrt(s)

Similar widths at sqrt(s) = 510 and 200 GeV for same x_E range and p_T^{trig} value



Larger widths at sqrt(s) = 510 than 200 GeV for same x_E range and x_T value



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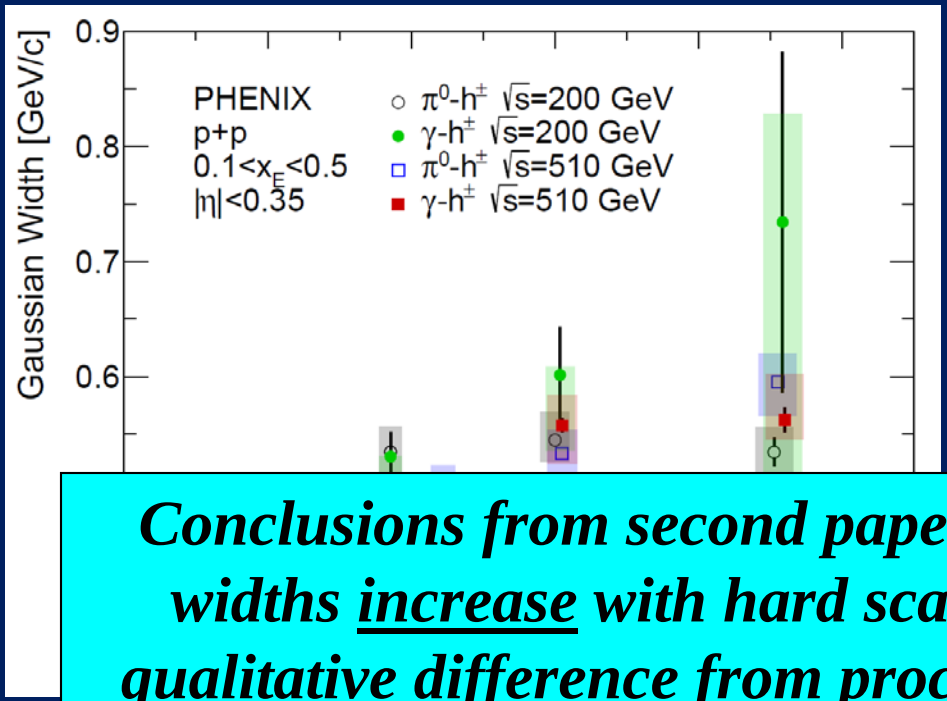
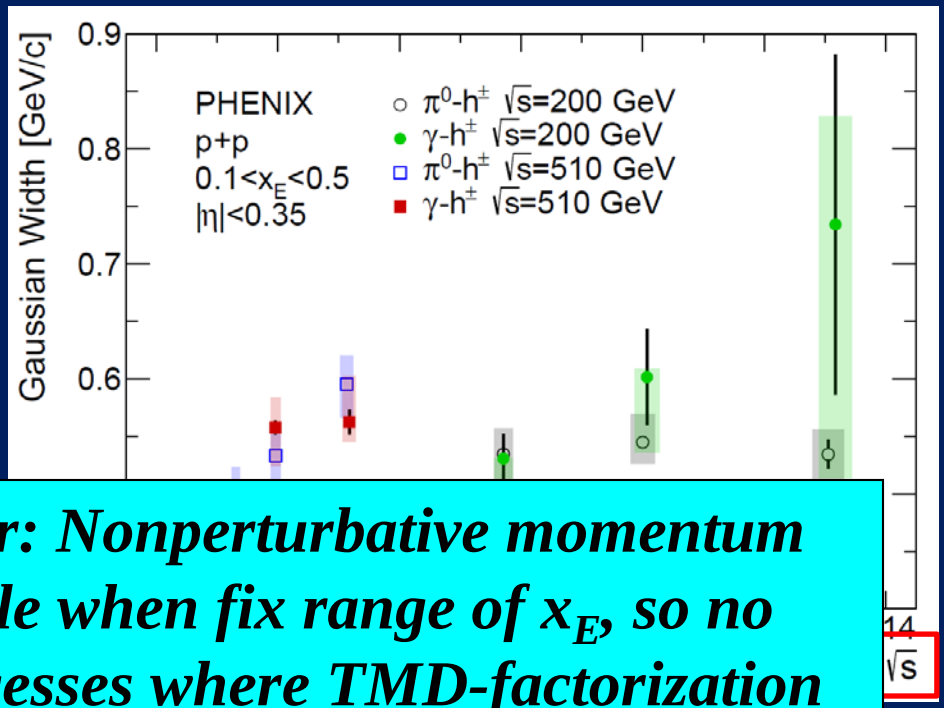
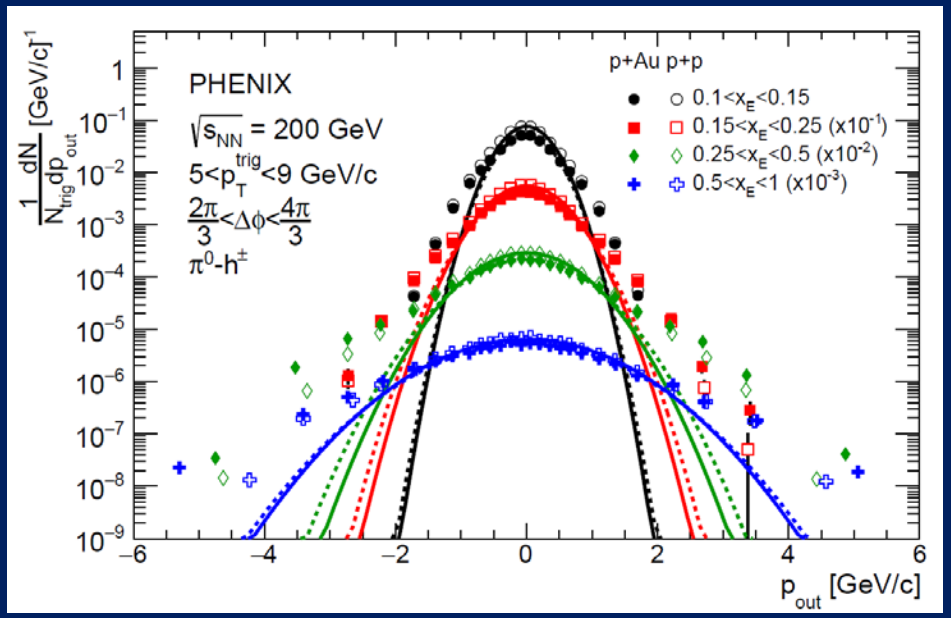




Conclusions from second paper: Nonperturbative momentum widths <u>increase</u> with hard scale when fix range of x_E, so no qualitative difference from processes where TMD-factorization holds. Still no calculations available for quantitative comparisons . . .

Third paper: Look for possible new/stronger effects in p+A collisions

- Nonperturbative widths *broadened* in p+Au compared to p+p



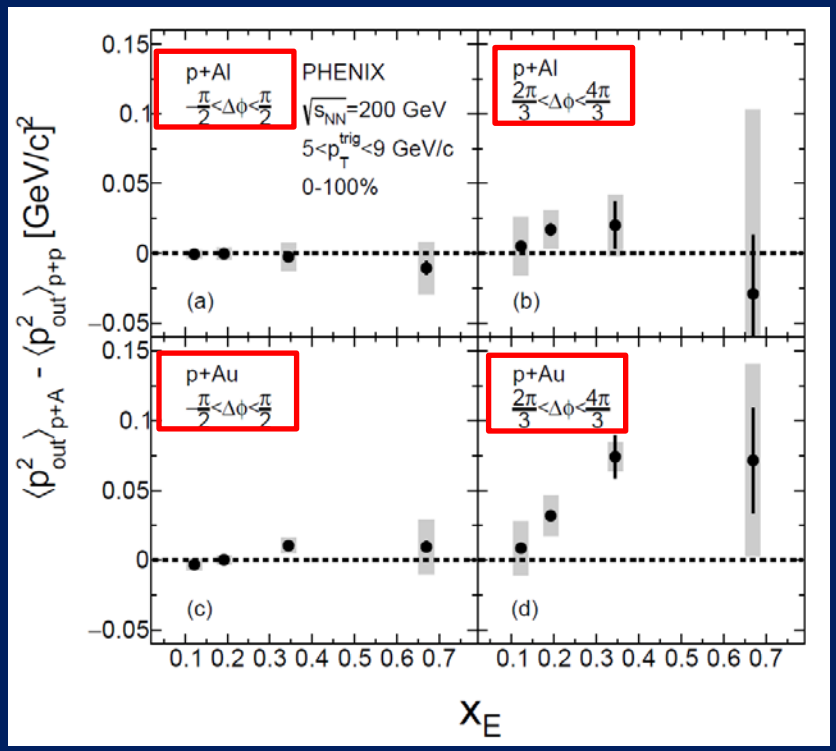
arXiv:1809.09045

Third paper: Look for possible new/stronger effects in p+A collisions

- Nonperturbative widths *broadened* in p+Au compared to p+p
- No significant broadening in p+Al
- No significant broadening in either p+Au or p+Al for hadrons near "trigger" hadron

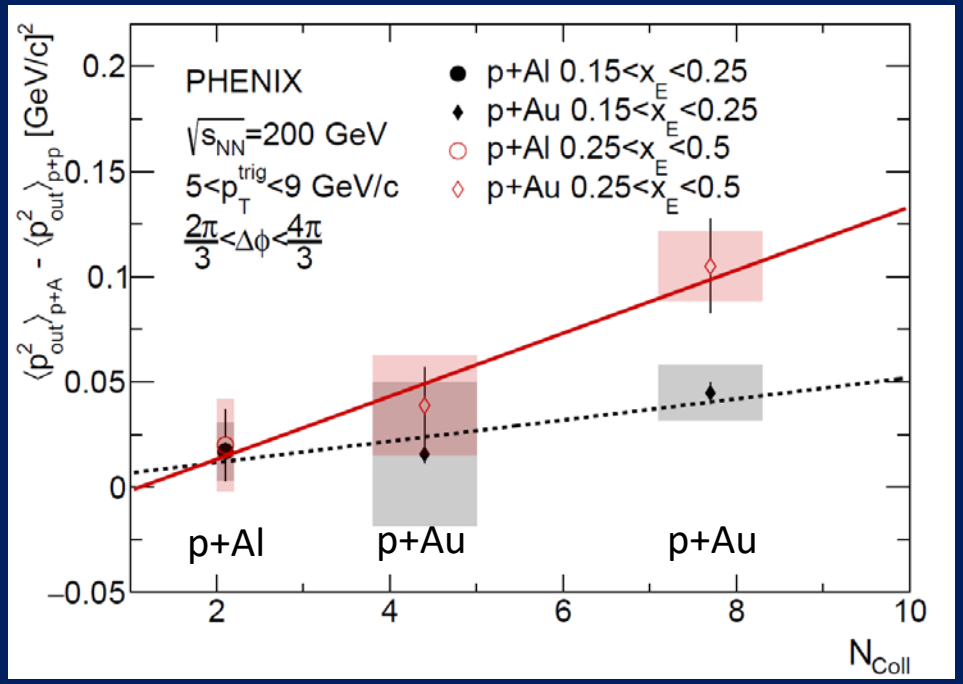
p+Al

p+Au



arXiv:1809.09045

Third paper: Evidence for centrality dependence of broadening



- Broadening of nonperturbative momentum widths in p+A compared to p+p observed to increase as a function of the number of estimated binary nucleon-nucleon collisions, based on backward (nucleus-going direction) multiplicities
- Broadening could be due to additional nonperturbative k_T in nuclei, multiple scattering in nuclei, nuclear modification of hadronization, . . .

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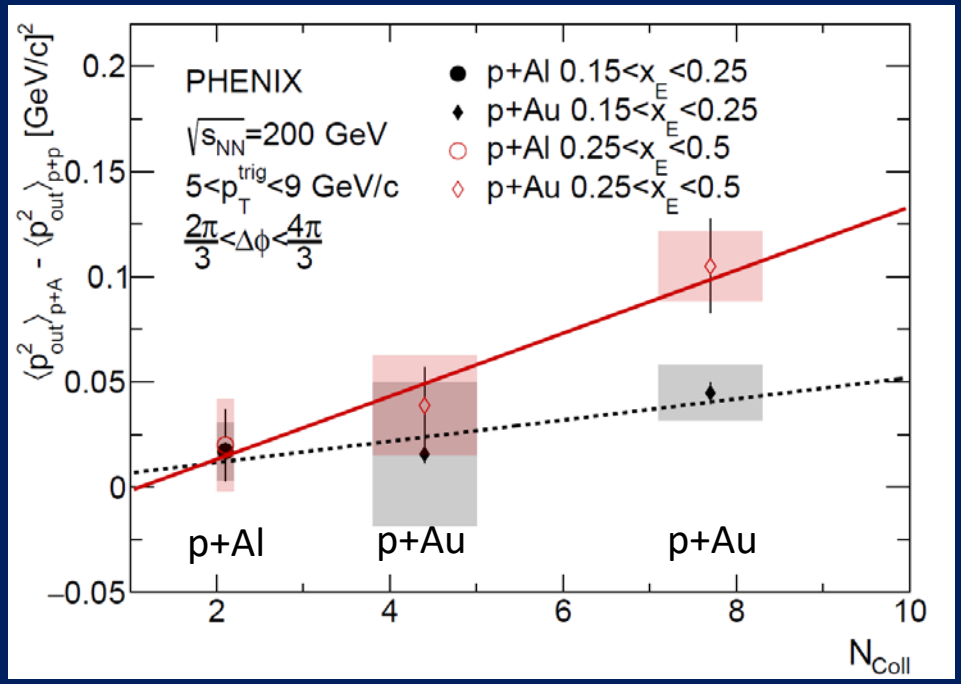

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See also Ph.D. thesis, J.D. Osborn, arXiv:1806.7763, for detailed results and discussion of dihadron and photon-hadron correlations in p+p (510 and 200 GeV), p+Al, p+Au (200 GeV)

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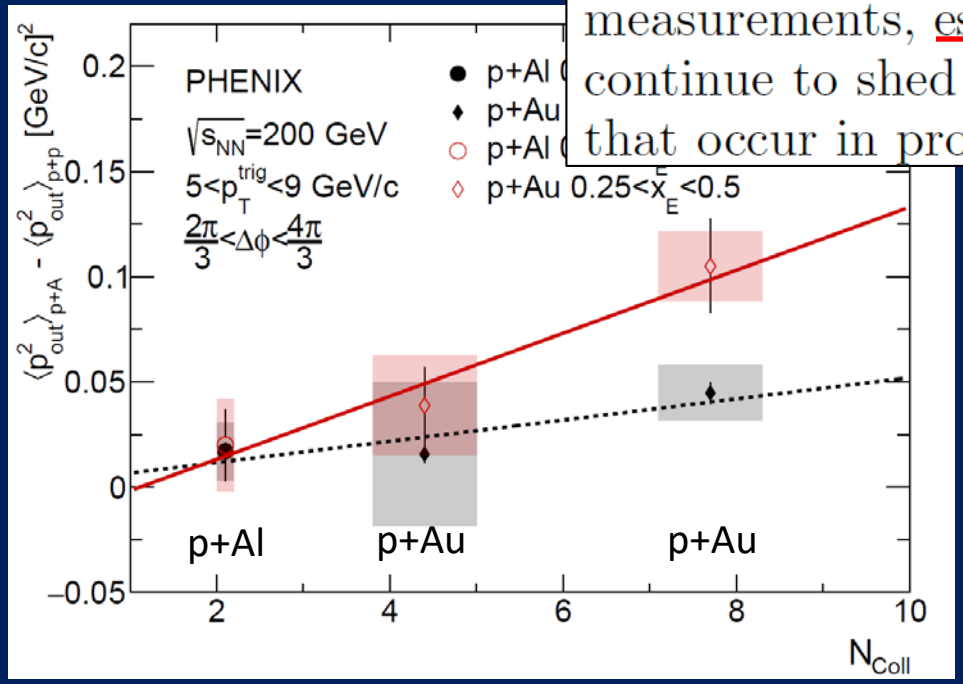

standing hadronic interactions involving nuclei. Future measurements, especially at an electron-ion collider, will continue to shed light on the many physical phenomena that occur in proton-nucleus collisions.

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Searching for TMD-factorization breaking at LHCb

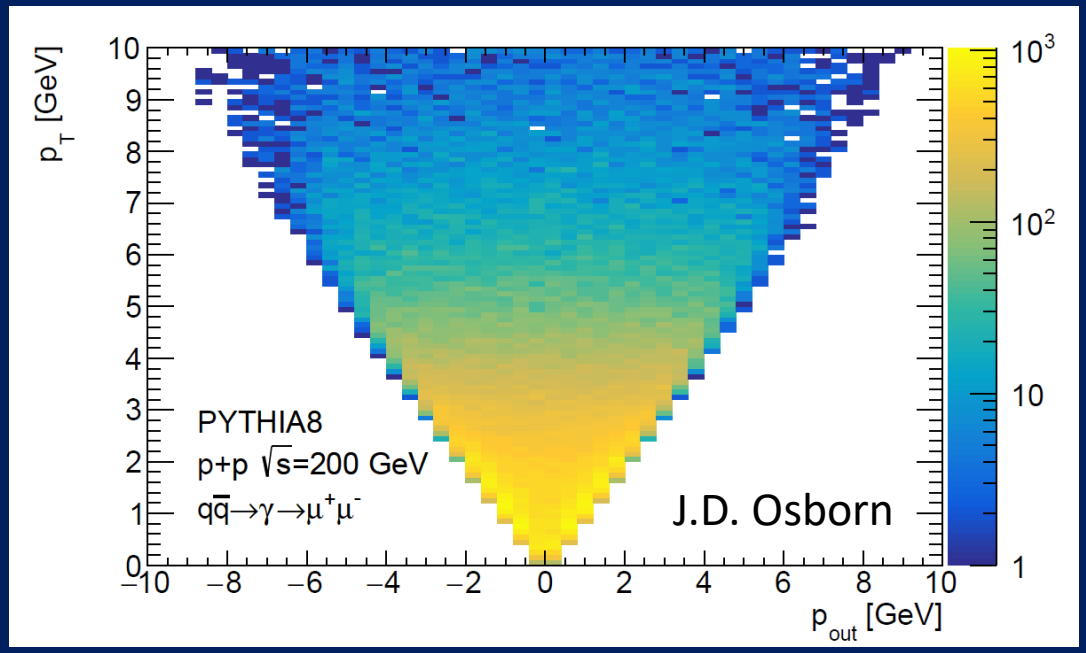
- We eagerly await phenomenological calculations assuming TMD-factorization holds, to make quantitative comparisons to PHENIX measurements! In the meantime . . .
- Just started working on similar dihadron, Z-hadron, and Z-jet measurements at LHCb
- In principle Z-jet measurements will give better handle on (LO) parton kinematics, but jets are more complicated objects than hadrons
  - Note that 2010 Rogers + Mulders paper was for dihadrons

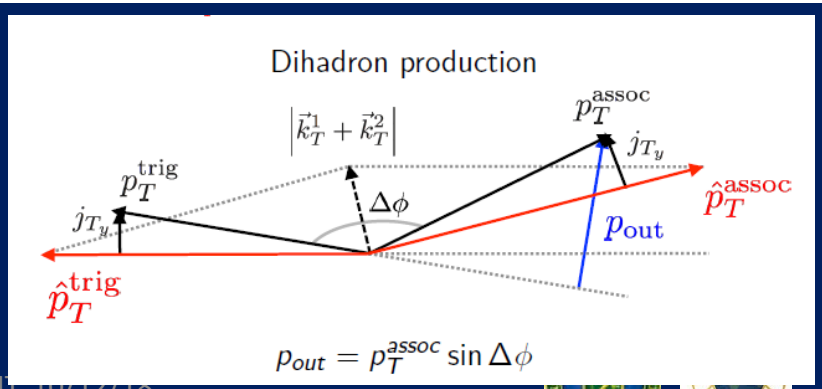
Searching for TMD-factorization breaking at LHCb: Drell-Yan as a comparison (and for TMD fitting)

- Also working on analogous Drell-Yan measurements at LHCb (TMD-factorization should hold)
- Will measure nonperturbative region of dilepton p_T, but also look at out-of-plane momentum widths for the dileptons, constructed exactly as for the dihadrons and Z-hadron measurements

Searching for TMD-factorization breaking at LHCb: Drell-Yan as a comparison (and for TMD fitting)

- Drell-Yan dilepton p_T vs. p_{out} from PYTHIA (RHIC c.m. energy)
- Possible to have p_{out} ~ 0 (nonperturbative) while pair p_T large (perturbative)—need to think through relation to parton k_T values . . .





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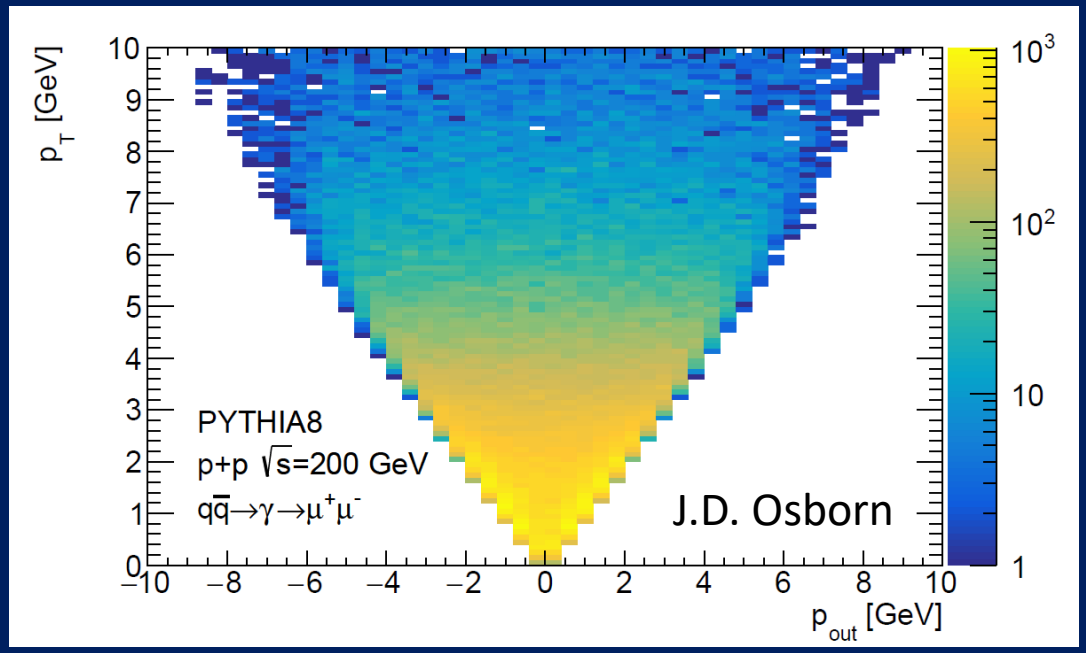

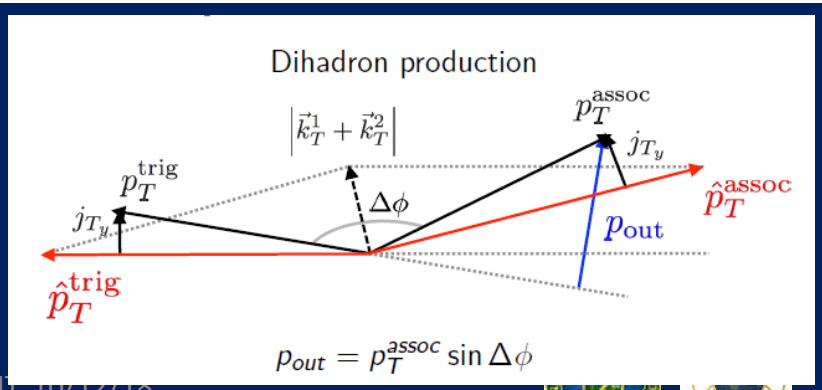

And yes, we should also be able to measure the p_T-dependent distribution for the upsilon

Exploring the role of color interactions in QCD

- Process-dependent sign change for PT-odd TMD functions and TMD-factorization breaking prediction both due to color flow in hadronic interactions

- Renewed/increasing interest in color interactions in recent years! Various motivations. Some examples of recent papers (not by any means comprehensive!) . . .

Further discussions of color entanglement

- A. Schaefer + J. Zhou PRD90, 094012 (2014) – "Color entanglement for gamma-jet in polarized p+A collisions"
  - "…the new gluon distribution function $G_4(x, k_T)$ generated by color entanglement"
  - Entanglement "can be seen not as a nuisance, but as a chance to explore the nontrivial interplay of color flow in local non-Abelian gauge theories"
- J. Zhou PRD96, 114001 (2017) – "Color entanglement like effect in collinear twist-3 factorization"

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Side note: A brief summary write-up of the various (proliferating?) gluon distributions might be helpful for some of us in the community

Quarkonium suppression in p+A; Collective behavior in high-multiplicity p+p

- Ma, Venugopalan, Watanabe, Zhang PRC97, 014909 (2018) – "Psi(2S) versus J/Psi suppression in proton-nucleus collisions from factorization violating soft color exchanges"

- Ortiz Velasquez, Christiansen, Cuautle Flores, Maldonado Cervantes, Paic PRL 111, 042001 (2013) – "Color reconnection and flowlike patterns in pp collisions"
- Ortiz, Palomo arXiv:1809.01744 - "Probing color reconnection with underlying event observables at the LHC energies"

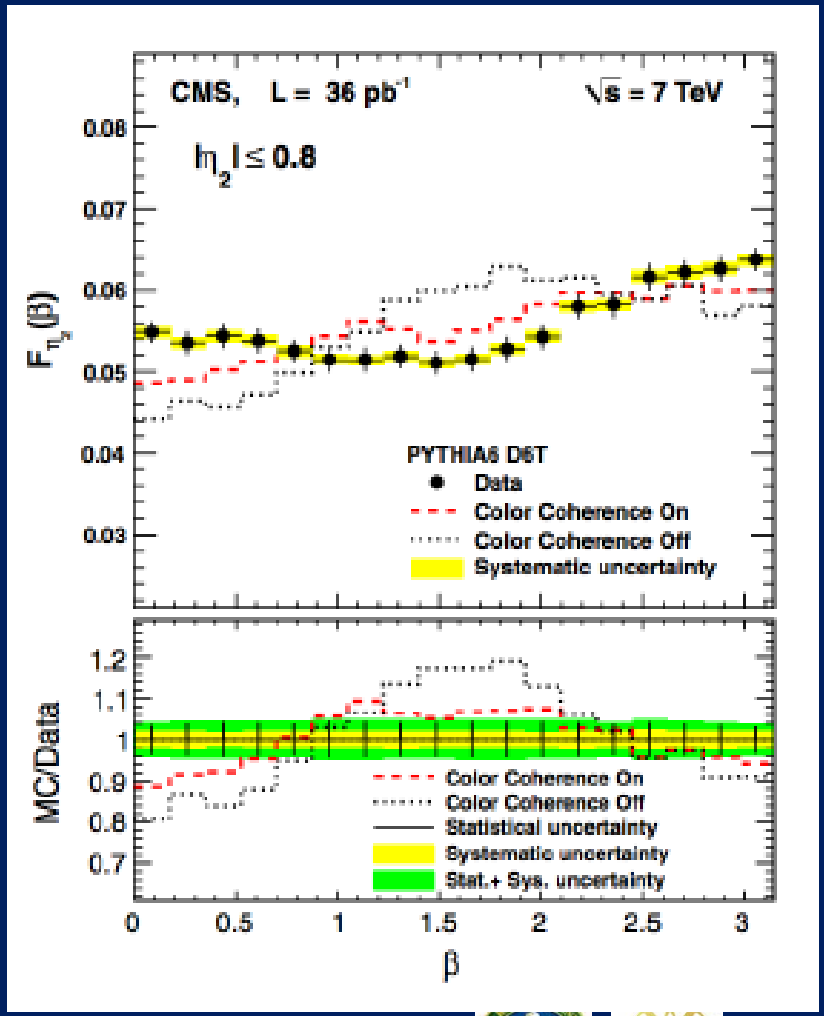
"Color coherence" in e+e-, p(bar)p

- "Color coherence" ideas about increased soft radiation between color-connected partons/remnants go back to e+e- measurements in the 1980s, e.g.
  - TPC/2*g* Collaboration, "Comparison of the Particle Flow in q-qbar-g and q-qbar-γ Events in e+e- Annihilation", Phys. Rev. Lett. 57, 945 (1986)
  - MARK2 Collaboration, "Comparison of the particle flow in Three-Jet and radiative Two-Jet Events from e+e- Annihilation at $E_{c.m.}$ = 29 GeV", Phys. Rev. Lett. 57, 1398 (1986)
  - OPAL Collaboration, "A study of coherence of soft gluons in hadron jets", Phys. Lett. B247, 617 (1990)
  - L3 Collaboration, "Evidence for gluon interference in hadronic Z decays", Phys. Lett. B353, 145 (1995)

- In 3-jet events in hadronic collisions, color coherence predicts that gluon radiation leading to lowest-p_T jet more likely to be in plane defined by emitting hard-scattered parton, i.e. "second" jet, and beam remnant, with stronger effects expected when second jet is closer to beam rapidity.

"Color coherence" in e+e-, p(bar)p

- D0, CDF, CMS have all published evidence for "color coherence effects"
  - CDF: PRD50, 5562 (1994) - "Evidence for color coherence in pp collisions at sqrt(s) = 1.8 TeV"
  - D0: PLB414, 419 (1997) – "Color coherent radiation in multijet events from pp collisions at sqrt(s) = 1.8 TeV"
  - CMS: EPJ C74, 2901 (2014) – "Probing color coherence effects in pp collisions at sqrt(s) = 7 TeV"



"Color coherence" in e+e-, p(bar)p

- ATLAS NPB918, 257 (2017) – "High-E_T isolated-photon plus jets production in pp collisions at sqrt(s) = 8 TeV with the ATLAS detector"
  - Measured isolated photon+(1, 2, or 3) jets – enhancements in QCD radiation "observed around the leading jet with respect to the photon in the directions towards the beams"

Using color correlations to reduce background in beyond-the-SM searches

- Gallicchio + Schwartz PRL 105, 022001 (2010) – "Seeing in Color: Jet Superstructure"
  - "the radiation on each end of a color dipole is being pulled towards the other end of the dipole"
  - Define "jet pull" observable based on color connection ideas

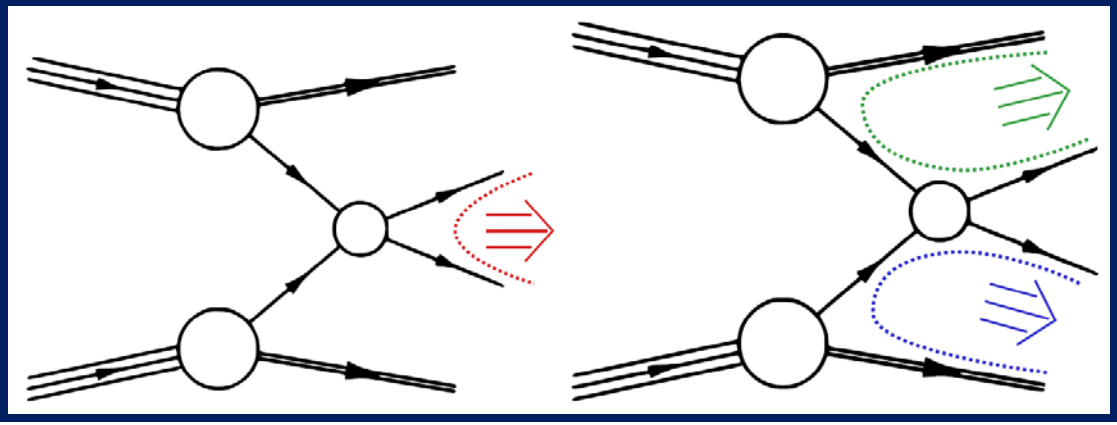


FIG. 1: Possible color connections for signal ($pp \to H \to b\bar{b}$) and for background ($pp \to g \to b\bar{b}$).

Using color correlations to reduce background in beyond-the-SM searches

- ATLAS measurement using Gallicchio-Schwartz proposal: PLB 750, 475 (2015) – "Measurement of colour flow with the jet pull angle in ttbar events using the ATLAS detector at sqrt(s) = 8 TeV"
  - "The jet pull angle is found to correctly characterise the W boson as a colour singlet"
  - A "proof-of-principle" measurement by ATLAS

Finding rigorous ways to work with color dynamics in QCD

- Color coherence/reconnection already implemented in Monte Carlo models for many years (and has certainly been very useful!). But also need to find ways to move toward rigorous QCD calculations

- Quantum computing one promising direction on EIC timescales? Unlike lattice, work directly in Minkowski space

Exploring color flow and interactions at the EIC

- Aside from color flow via PT-odd TMD functions (old news) . . .
- Measurements similar to “color coherence” studies done in e+e-, p+p, and p+pbar will certainly be possible, e.g. hadrons between a produced jet and the direction of the hadronic beam remnant
- Maybe through other more exclusive DIS measurements, e.g. measure enough of the final state to be sensitive to color correlations between current and target fragmentation regions?

Exploring color flow and interactions at the EIC

- Explore different hadronization mechanisms—and therefore different color neutralization mechanisms—in e+p, e+A, p+p, p+A, and A+A, e.g. “vacuum fragmentation” vs. “recombination”/“coalescence” in parton-rich environments (including high-multiplicity small systems?)

- … ???

Exploring color flow and interactions at the EIC

- Will need to identify well-defined observables

- As often in QCD, may be easier to isolate specific effects in simpler collision systems. Therefore comparing measurements sensitive to color interactions at the EIC to p+p, p+A, and A+A will be important, but e+e- measurements could likely be quite useful to compare in turn to e+p and e+A, or use as input for more complex QCD systems
  - E.g. studying correlations among low-z hadrons in e+e-?
  - Old e+e- measurements worth repeating with modern experiments?

Speculation

- Will thinking about color interactions that break factorization help us develop new pictures of hadronic interactions that aren't limited to high-energy approximations? E.g. d.o.f. that aren't associated with single partons, or even a partonic picture per se? Particle vs. field pictures of color interactions?
  - We eventually want to be able to go smoothly between different regimes in QCD, different pictures of hadrons, both mathematically and conceptually…

Summary

- First exploratory measurements searching for TMD-factorization breaking/color entanglement have been performed by PHENIX
  - Awaiting phenomenological calculations assuming factorization holds to search for deviations from data!
  - Follow-up measurements getting started at LHCb
- There is renewed/increased interest in color interactions in QCD, with motivations coming from several different communities in nuclear and HEP

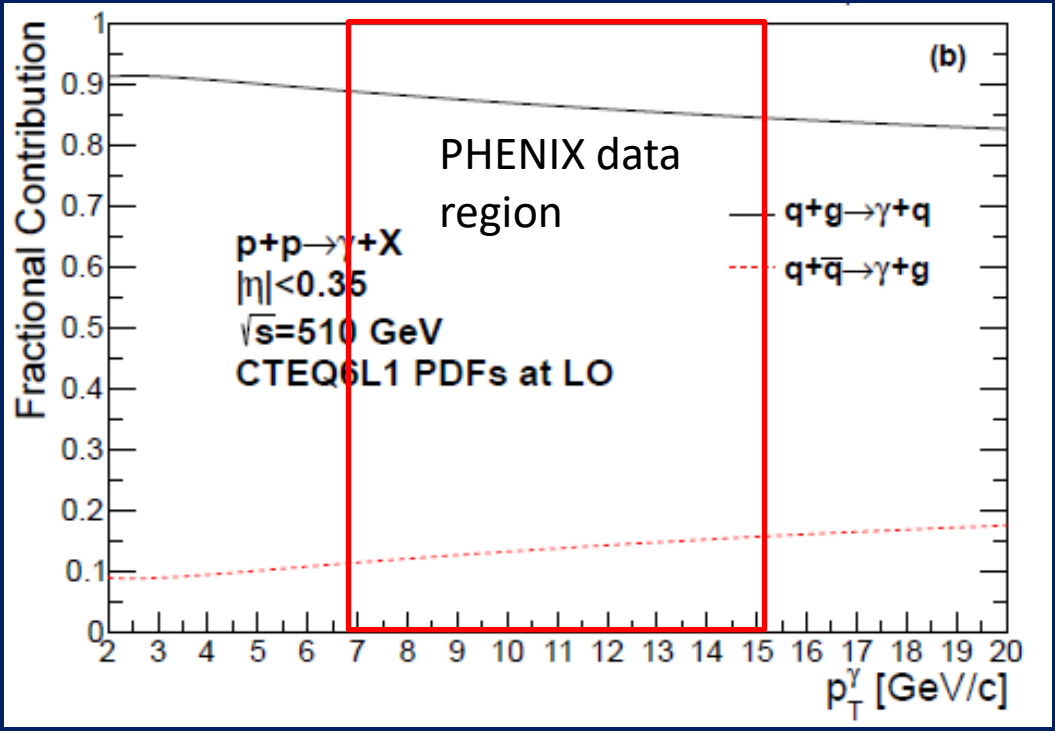
Summary

- First exploratory measurements searching for TMD-factorization breaking/color entanglement have been performed by PHENIX
  - Awaiting phenomenological calculations assuming factorization holds to search for deviations from data!
  - Follow-up measurements getting started at LHCb
- There is renewed/increased interest in color interactions in QCD, with motivations coming from several different communities in nuclear and HEP

Lots of new territory to explore as we start to think in more detail, and in new ways, about color and color interactions in QCD! The EIC will surely provide new opportunities as we develop our ideas further.

Extra

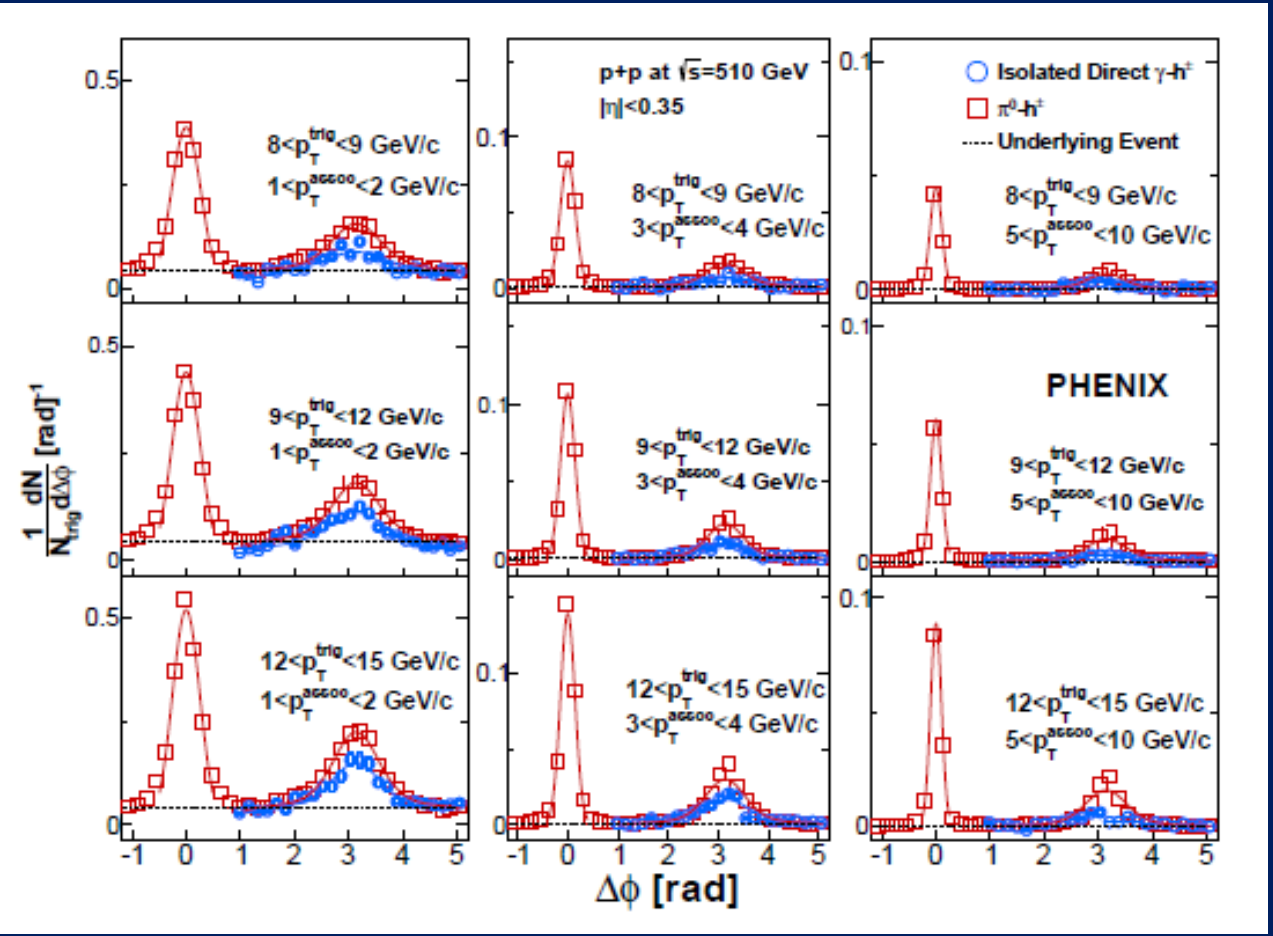
Partonic process contributions for direct photon production



Quark-gluon Compton scattering still dominates at NLO - PLB140, 87 (1984)

PHENIX Collab., arXiv:1609.04769,
Submitted to PRD.
Calculation by T. Kaufmann

Two-particle correlation distributions show expected jet-like structure

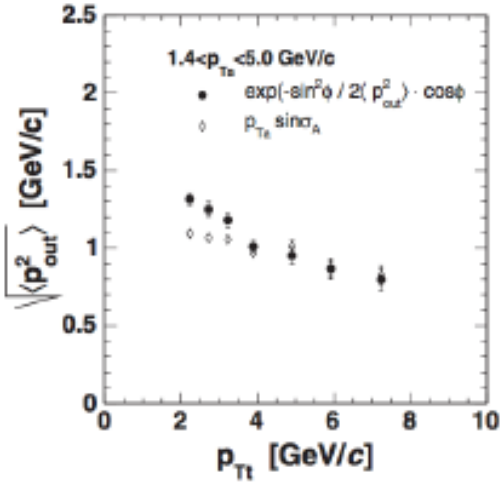


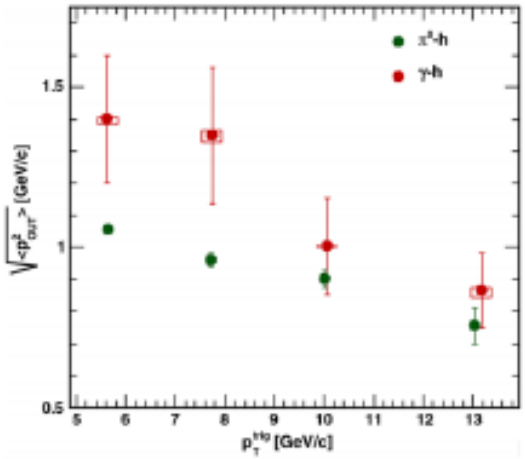
PRD95, 072002 (2017)

Other measurements showing decreasing nonperturbative momentum widths

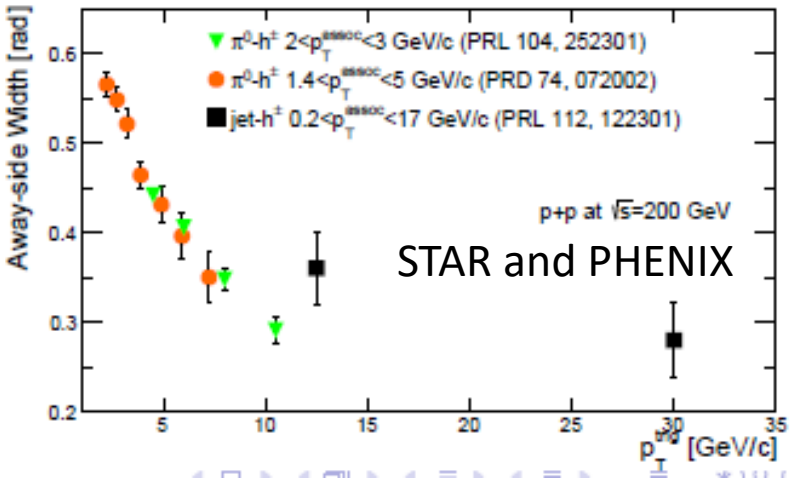
- Other RHIC publications show the same effect in $\sqrt{\langle p_{out}^2 \rangle}$ and away-side width
- All previous analyses motivated by different physics goals: fragmentation functions, partonic energy loss in QGP, etc.

PRD 74, 072002 (2006) (PHENIX)





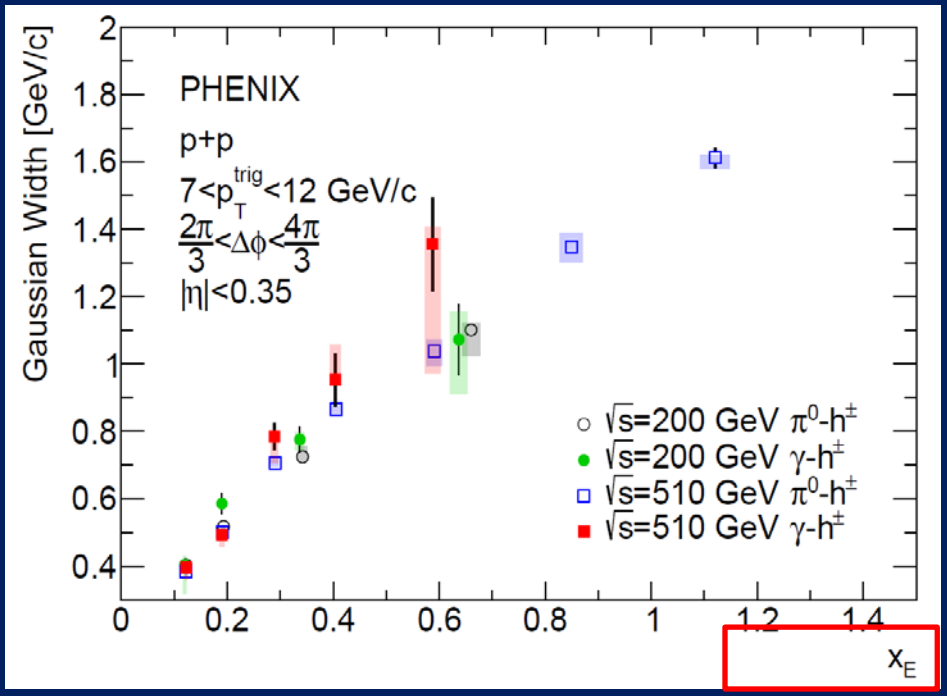
PRD 82, 072001 (2010) (PHENIX)



STAR and PHENIX

Second paper: Comparison of different sqrt(s)

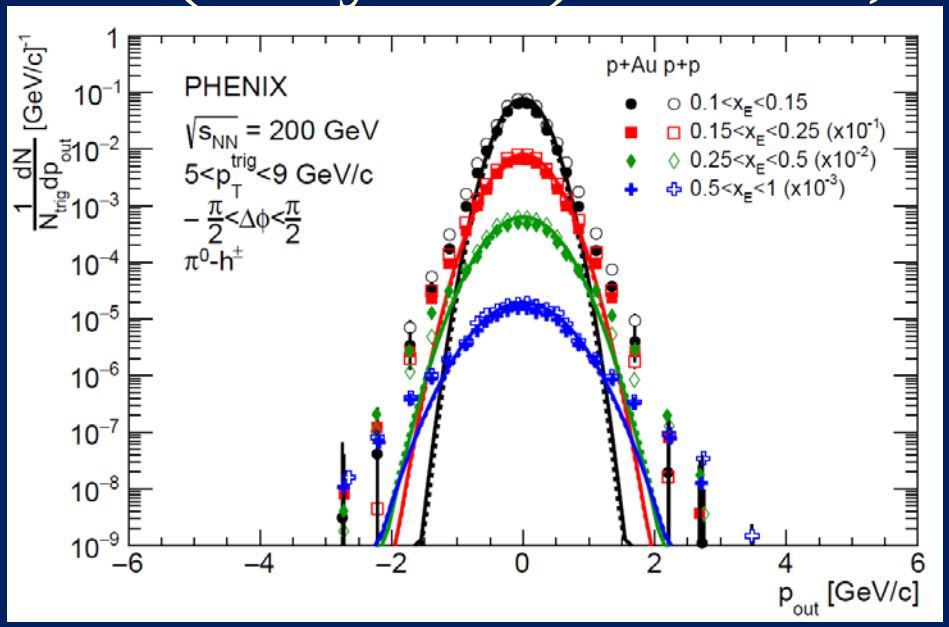
Similar widths at sqrt(s) = 510 and 200 GeV for same p_T^{trig} range and x_E value

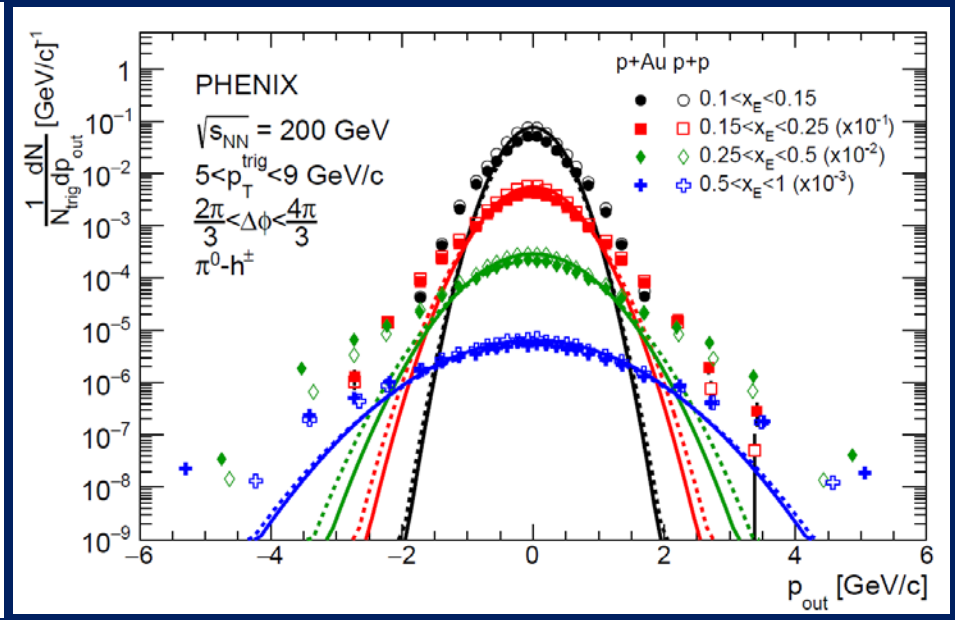


arXiv:1805.02450, accepted by PRD

Third paper: Look for possible new/stronger effects in p+A collisions

- Nonperturbative widths broadened in p+Au compared to p+p for nearly back-to-back (away-side) hadrons, but not near-side hadrons

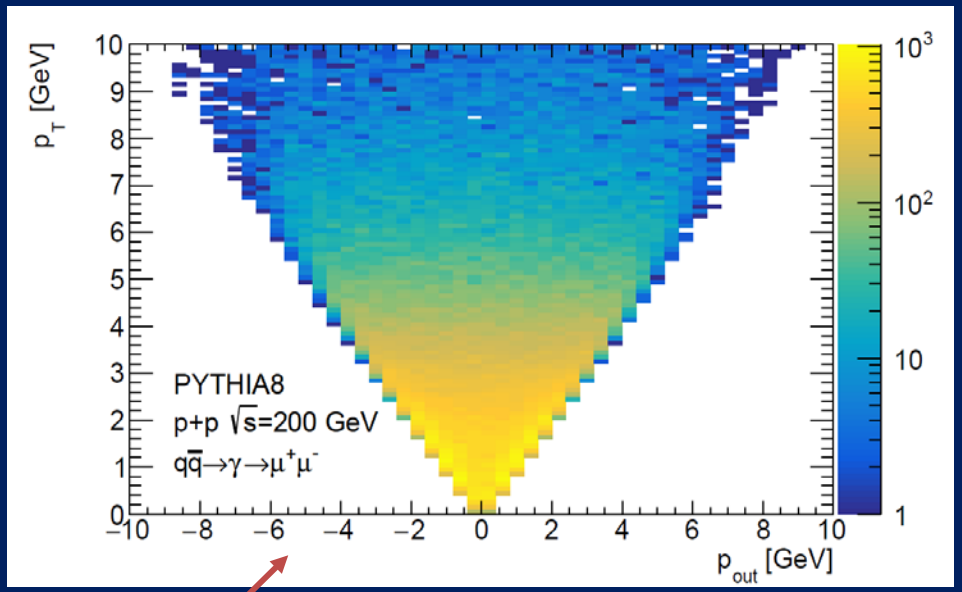


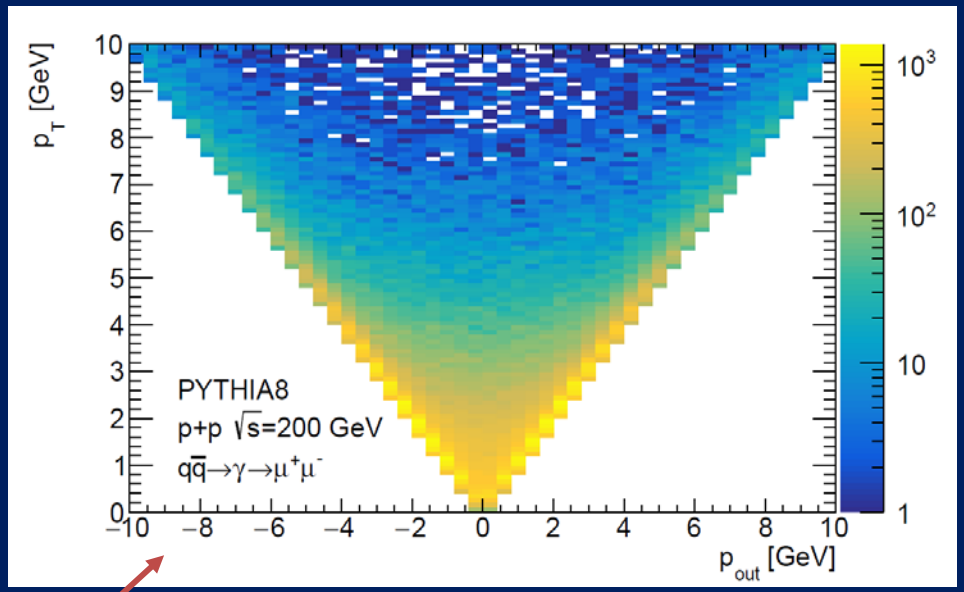


arXiv:1809.09045

Drell-Yan p_T vs. p_{out} for the two choices of "trigger" lepton

J.D. Osborn





Higher-p_T lepton taken as "trigger"

Lower-p_T lepton taken as "trigger"